

A Beam Splitter for Guided Atoms on an Atom Chip

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(March 31, 2000)

Abstract

We have designed and experimentally studied a simple beam splitter for atoms guided on an *Atom Chip*, using a current carrying Y-shaped wire and a bias magnetic field. This beam splitter and other similar designs can be used to build atom optical elements on the mesoscopic scale, and integrate them in matterwave quantum circuits.

PACS numbers: 03.75.Be, 03.65.Nk

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Beam splitters are key elements in optics and its applications. In atom optics [1] beam splitters were, up to now, only demonstrated for atoms moving in free space, interacting either with periodic potentials (spatial and temporal), or semi transparent mirrors [2]. On the other hand, guiding of atoms has attracted much attention in recent years and different guides have been realized using magnetic potentials [3–8], hollow fibers [9], and light potentials [10,11].

In this letter we describe experiments which join the above, namely demonstrating a nanofabricated beam splitter for guided atoms using microscopic magnetic guides on an *Atom Chip* (see Fig. 1).

By bringing atoms close to electric and magnetic structures, one can achieve high gradients to create microscopic potentials with a size comparable to the de-Broglie wavelength of the atoms, in analogy to mesoscopic quantum electronics [12,13]. It is possible to design quantum wells, quantum wires and quantum dots for neutral atoms and further combine these elements to form more complex structures. A large variety of these microscopic potentials can be designed by using the interaction $V = -\vec{\mu} \cdot \vec{B}$ between a neutral atom with magnetic moment $\vec{\mu}$ and the magnetic field \vec{B} generated by current carrying structures [5,14,15]. Mounting the wires on a surface, allows elaborate designs with thin wires which can sustain sizable currents [15]. Such surface mounted atom optical elements were recently demonstrated for large structures (wire size $\approx 100\mu m$) [6,16,17], and nanofabricated structures [8], the latter achieving the scales required for mesoscopic physics and quantum information proposals with microtraps [18].

The simplest configuration for a magnetic guide is a straight current carrying wire [3,4,14]. The magnetic field at a distance r from the wire is given by $B = \frac{\mu_o}{2\pi} \frac{I}{r}$, where I is the wire current. Atoms in the high field seeking state are guided in Kepler orbits around the wire (Kepler guide). By adding a homogeneous bias field one can produce a 2-dimensional minimum of the potential at a distance $\frac{\mu_o}{2\pi} \frac{I}{B_{bias}}$ from the wire [19] and guide atoms in the low field seeking state (side guide).

By combining two of these guides, it is possible to design potentials where at some

point two different paths are available for the atom. This can be realized using different configurations, among which the simplest and most advantageous is a Y-shaped wire (Fig. 1a) [20]. Such a beam splitter has one accessible input for the atoms, that is the central wire of the Y, and two accessible outputs corresponding to the right and left wires. Depending on how the current I in the input wire is sent through the Y, atoms can be directed to the output arms of the Y with any desired ratio (Fig. 1b).

The Y beam splitter can be created either as a Kepler guide or as a side guide. We previously performed preliminary experiments studying such a beam splitting potential using free standing wires [5]. In the experiment reported here, we study a beam splitter created by a Y-shaped wire on a nano-fabricated *Atom Chip*.

Our experiments are carried out using laser cooled Li atoms. A detailed description of the apparatus and the atom trapping procedure is given in [8,21].

The *Atom Chip* consists of a $2.5\mu\text{m}$ thick gold layer deposited onto a GaAs substrate. This gold layer is patterned using standard nanofabrication techniques. A schematic of the wires on the *Atom Chip* used for this experiment is shown in Fig. 1a. It includes, besides the beam splitter, a series of magnetic traps to transfer atoms into smaller and smaller potentials: the large U-shaped wires are $200\mu\text{m}$ wide and provide a quadrupole potential if combined with a homogeneous bias field [8,17,22], while the thin Y-shaped wire is $10\mu\text{m}$ wide. An additional U-shaped 1mm thick wire is located underneath the chip in order to assist with the loading of the chip.

The atoms are loaded onto the *Atom Chip* using our standard procedure (see details in [8]): Typically 10^8 cold ^7Li atoms are accumulated in a "reflection MOT" [23–25] and transferred to the splitting potential in the following steps: Atoms are first transferred into the MOT generated by the quadrupole field of the U-wire ($I=17\text{A}$, $B_{\text{bias}}=6\text{G}$) underneath the chip. Then, the laser light is switched off, leaving the atoms confined only by the magnetic quadrupole field of the U-wire. Atoms are then further compressed and transferred into a magnetic trap generated by the two $200\mu\text{m}$ wires on the chip ($I=2\text{A}$, $B_{\text{bias}}=12\text{G}$), compressed again and transferred into the $10\mu\text{m}$ guide ($I=0.8\text{A}$, $B_{\text{bias}}=12\text{G}$). Each compression

is achieved by decreasing the current generating the larger trap to zero and simultaneously switching on the current generating the smaller trap over a time of 10ms. Typically we transfer $> 10^6$ atoms into the $10\mu m$ guide [26], which has a typical transverse trap frequency of $\omega = 2\pi \times 6kHz$.

The properties of the beam splitter are investigated by letting the atoms propagate along the guide for some time due to their longitudinal thermal velocity. The resulting atom distribution is measured by fluorescence images taken by a CCD camera looking at the atom chip surface from above. For this a short ($< 0.5ms$) molasses pulse is applied. The pictures shown in Fig. 1b are such images taken after 16ms of guiding in the beam splitter. The first two pictures are obtained at $B_{bias}=12G$ by sending 0.8A only through one of the output wires; atoms can therefore turn either left or right. In the third and fourth pictures the atoms experience a splitting potential, the current being sent equally through both out-going arms of the Y-shaped wire. The images are taken at bias field 12G and 8G respectively. At 12G the atoms are clearly more compressed.

By changing the current ratio between the two outputs, and simultaneously keeping the total current constant, it is possible to control the probability of going left and right. Typical data for a beam splitter experiment using 8G bias field are shown in Fig. 2. Here, the number of atoms in each arm is determined by summing over the density distribution. When the current is not balanced, the side carrying more current is preferred due to the larger transverse size of the guiding potential. It can be noted that the 50/50 atomic splitting ratio occurs for a current ratio different from one half. This is due to an additional 3G field directed along the input guide to make a Ioffe-Pritchard configuration and prevent Majorana spin flips; such a field introduces a difference in the output guides which can be compensated with different currents. The solid lines shown in Fig. 2 are obtained with Monte Carlo simulations of an atomic sample at $T=250\mu K$ propagating in the Y beam splitter.

Before discussing the Y beam splitter in detail, one should note some properties of the beam splitting potential created by the Y-shaped wire and a homogeneous bias field as shown

in Fig. 3: (1) For the in-coming arm of the Y and for the two out-going arms, far away from the splitting point, we have simple side guide potentials. (2) The potential for the two out-going guides is tighter than for the in-coming guide and its minimum is at half distance from the chip surface. This is caused by the fact that the in-coming guide is formed by a current which is twice that of the out-going guides. It should also be noted that due to the change in direction of the output wires, the bias field has now a component along the guides which contributes to the Ioffe-Pritchard field. (3) The splitting point of the potentials is *not* at the geometrical splitting point of the wires. This can be seen in the pictures of Fig. 1b. The actual split point of the potential is located after the geometrical split. Precisely, it occurs when the distance between the output wires is given by $d_{split} = \frac{\mu_o}{2\pi} \frac{I}{B_{bias}}$, which is equal to the height above the chip of the input guide. (4) An additional potential minimum appears between the geometric splitting point of the Y-wire and the splitting point of the potential, forming a fourth port.

The different location of the potential split, and the additional inaccessible fourth port of the beam splitting potential, can be explained simply by taking two parallel wires with current in the same direction and adding a homogeneous bias field along the plane containing the wires and directed orthogonal to them. Depending on the distance d between the wires one observes three different cases: (i) if $d < d_{split}$, two minima are created one above the other on the axis between the wires. In the limit of d going to zero, the barrier potential between the two minima goes to infinity (in approximation of infinitely thin wires) and the minimum closer to the wires plane falls onto it. (ii) if $d = d_{split}$, the two minima fuse into one. (iii) if $d > d_{split}$ two minima are created one above each wire. The barrier between them increases with the wire distance and we eventually obtain two independent guides. In the Y beam splitter one encounters all three cases moving along the beam splitter axis. This is shown in detail in Fig. 3b and c, which present two projections, onto the beam splitter plane and orthogonal to it respectively.

The dynamic of an atom propagating through the Y beam splitter potential is best described by a scattering process in restricted space from in-coming modes into out-going

modes. As in most scattering processes in free space, we expect some back scattering into the in-coming mode. Additional back scattering mechanisms due to the guides also occur: For instance, the output guides have higher transverse gradients because each of them carries half of the current. This gives rise to a reflection probability due to a mismatch of modes. Another contribution comes from the direction change of the input guide as it gets closer to the chip surface. From the atomic distribution observed in the experiment we could estimate a back-reflection of less than 20% at the splitting point. This may be further minimized by varying the potential shape and choosing different geometries. In addition the fourth port, caused by the second minimum before the split point, induces a loss rate since atoms taking that route will hit the surface.

The Y configuration enables a 50/50 splitting over a wide range of experimental parameters due to its *inherent symmetry* relative to the incoming guide axis, where by inherent we mean that the symmetry of the potential is maintained for different magnitudes of current and bias field, and for different incoming transverse modes. This was also numerically confirmed up to the first 35 modes. The atom arriving at the splitting junction encounters a symmetric scattering potential, and will thus have equal right-left amplitudes regardless of the specific current and bias field in use. Therefore, such a beam splitter should allow inherently coherent splitting for multi-mode propagation. This symmetric splitting may only be corrupted by breaking the symmetry of the potential, for example by a rotation of the bias field direction, or with a current imbalance.

This is an advantage over beam splitter designs for guided matter waves which rely on tunneling [27]. In such a configuration, two side guides coming close together and going apart again, the potential at the closest point exhibits two guides separated by a potential barrier. Here the disadvantage is that the splitting ratio for an incoming wave packet is vastly different for different propagating modes, since it depends strongly on the tunneling probability. A further disadvantage is that, even for single mode splitting, the barrier width and height and consequently the splitting amplitudes are extremely sensitive to changes in the current and bias field.

The back scattering and the inaccessible fourth port of the Y beam splitter may be, at least partially, overcome using different beam splitter designs like the ones shown in Fig. 4. The configuration shown in Fig. 4a has two wires which run parallel until a given point and then go apart. In case the bias field is chosen to exactly fulfill case (ii) of the above discussion, the splitting point of the potential is ensured to be that of the wires and the height of the potential minimum above the chip surface is maintained throughout the device (in the limit of small opening angle). Furthermore, no fourth port appears in the splitting region. In Fig. 4b we present a more advanced design. Here a wave guide is realized with two parallel wires with currents in opposite directions and a bias field perpendicular to the chip surface. The splitting potential is designed in order to have input and output guides with identical characteristics, therefore eliminating reflections due to different guide gradients. On the other hand, this multi-wire configuration might be more difficult to integrate in a complex network.

In conclusion, we have realized a beam splitter for guided atoms, with a design that ensures symmetry under a wide range of experimental parameters, and which we have shown can be further developed to bypass the main drawbacks. This device could find applications in atom interferometry and in the study of decoherence processes close to a surface. Furthermore, this basic element could be integrated into more complex quantum networks which would form the base for advanced applications such as quantum information processing.

We would like to thank A. Chenet, A. Kasper, S. Schneider and A. Mitterer for help in the experiments. *Atom Chips* used in the preparation of this work and in the actual experiments were fabricated at the Institut für Festkörperelektronik, Technische Universität Wien, Austria, and the Sub-micron center, Weizmann Inst. of Science, Israel. We thank E. Gornik, C. Unterrainer and I. Bar-Joseph of these institutions for their assistance. This work was supported by the Austrian Science Foundation (FWF), project SFB F15-07, and by the ACQUIRE collaboration (EU, contract Nr. IST-1999-11055). B.H. acknowledges financial support from Svenska Institutet.

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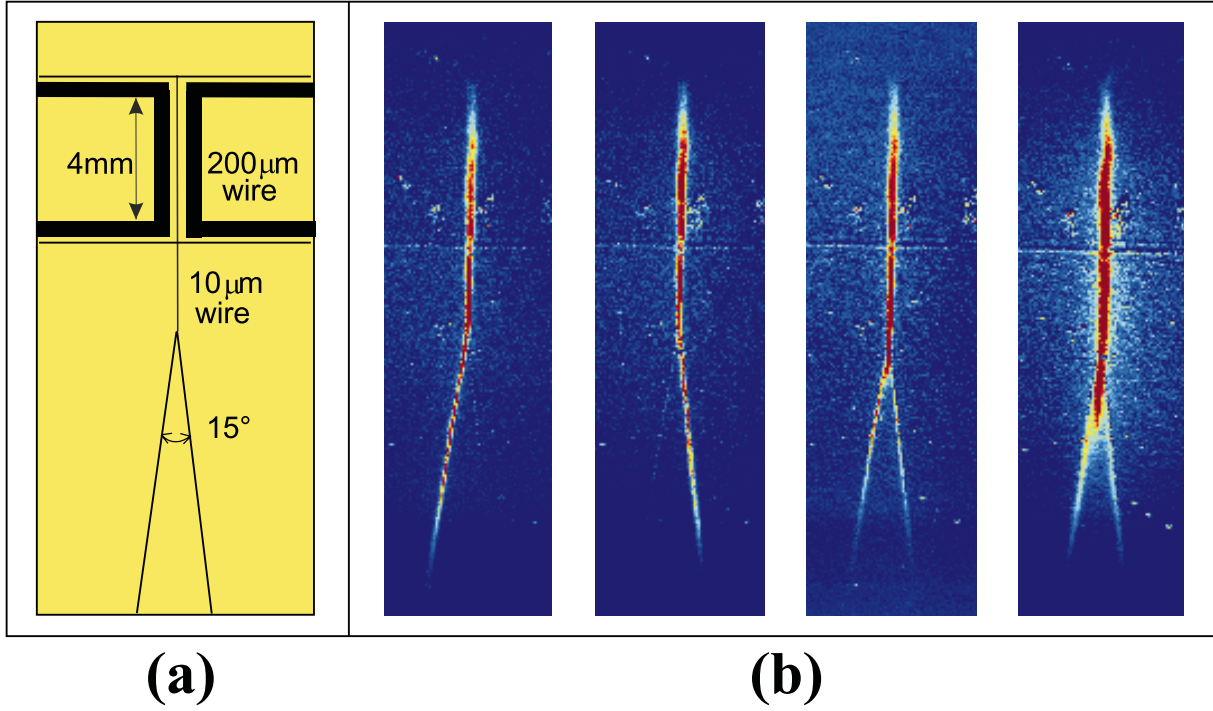


FIG. 1. Beam splitter on a chip: (a) chip schematic and (b) fluorescence images of guided atoms. As explained in the text, the two large U-shaped $200\mu m$ wires are used to load atoms onto the $10\mu m$ Y-shaped wire. In the first two pictures in (b), we drive current only through one side of the Y, therefore guiding atoms either to the left or to the right; in the next two pictures, taken at two different guide gradients, the current is divided in equal parts and the guided atoms split into both sides.

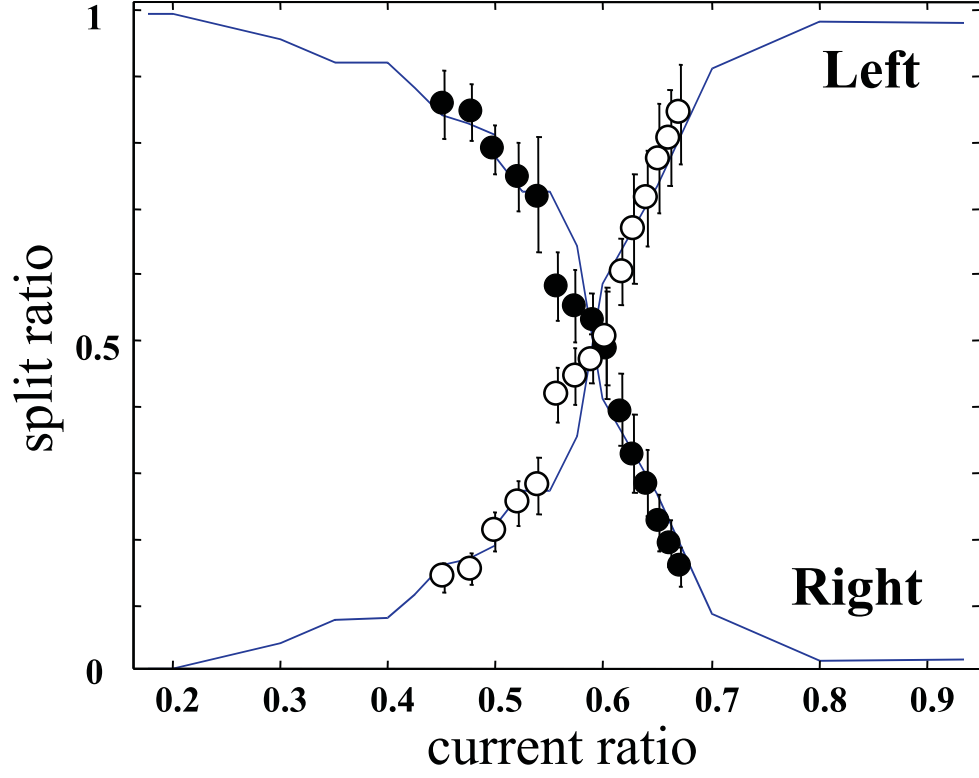


FIG. 2. Switching atoms between left and right by changing the current ratio in the two outputs and keeping the total current constant at 0.8A. The points are measured values while the lines are obtained from MC simulations. The kinks in the lines are due to MC statistics.

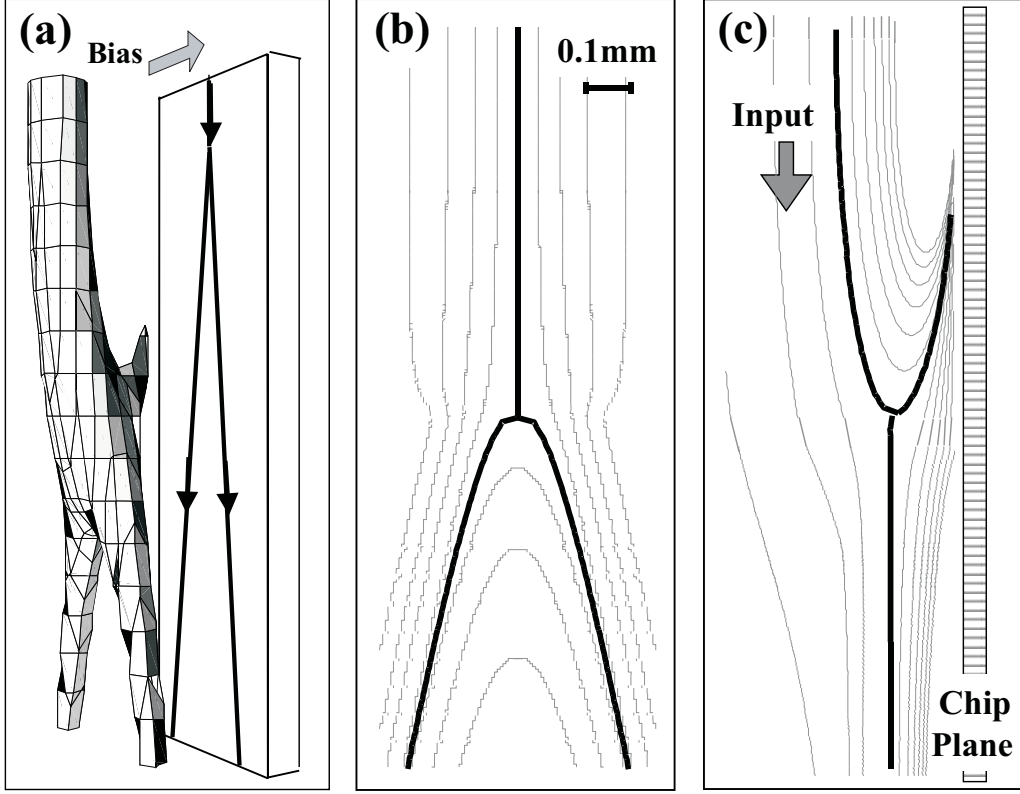


FIG. 3. Detailed properties of the Y splitting potential: (a) shows the 1.5G equipotential surface above the *Atom Chip* surface; (b) shows the position of the potential minima (black line) projected onto the surface; (c) shows the minima location above the surface. A second minimum closer to the chip surface occurs in the region between the wire splitting and the actual split point of the potential. In (b) and (c) the gray dotted lines are equipotential lines. These plots are generated at wire current 0.8A and $B_{bias}=6G$.

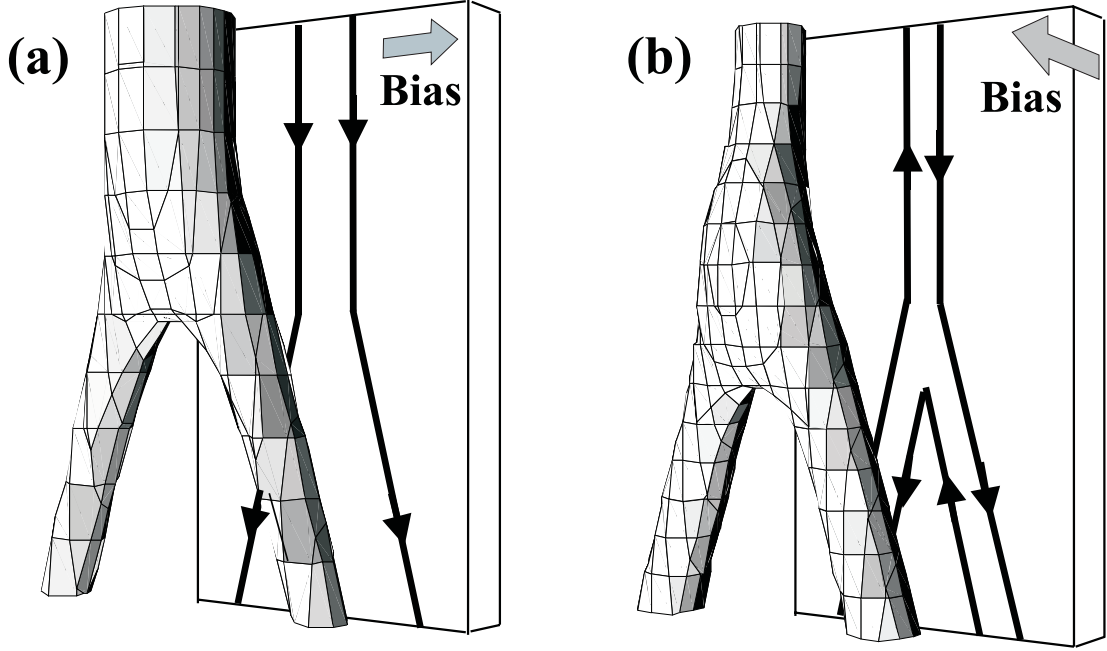


FIG. 4. Y beam splitter designs: The splitting potential in (a) is realized with two wires running parallel until a given point and then going apart; (b) is a more advanced Y beam splitter where the output guides have the same characteristics as the input guide, in order to minimize the back-scattered amplitude.